From Land Cover to Land Use: A Methodology for Efficient Land Use Mapping over Large Areas

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Land use information over large areas is increasingly important for many studies related to environment in general and global change in particular. Yet there is a dearth of methodological knowledge in this area, especially regarding the practical task of producing land use maps. In this article, a systematic land use mapping approach is developed, based on land cover maps that in turn are produced through remote sensing. The concept is based on the recognition of varying strengths of land cover (LC)–land use (LU) relationships, from the thematic and spatial points of view. Several categories of relationships are identified, ranging from direct (case 1) to multiple/complex (case 4), and appropriate mapping strategies are discussed for these cases. Using a mapping study in Lebanon, it is shown that the principles embodied in this approach correspond to issues and conditions in real mapping situations. Finally, the concepts are translated into a series of steps through which the method can be applied to large areas, taking into consideration the specific requirements and constraints of each case. The final land use map represents an acceptable compromise between accuracy, level of detail, and cost. **Key Words: land cover, land use, methods, remote sensing.**

Introduction

Land cover (hereafter LC) and land use (LU) are two key elements that describe the terrestrial environment in natural and human-activity-related terms, respectively. LC may be of natural origin, such as forest, glaciers, rivers and other open water bodies, or bare soil or rock. However, it may also be created by LU, e.g., buildings, roads, or water reservoirs. LC is characterized by the biophysical features of the terrestrial environment, typically based on a classification system consisting of discrete classes and formulated for a specific purpose. LU refers to the manner in which these biophysical assets are used by people. It is the employment of LC and management strategy used on a specific LC type by human agents, or land managers (Baulies and Szejwach 1997). The term LU may also describe the intent with which a particular LC was formed. For example, a body of water may be a hydroelectric reservoir, a grass-covered area a golf course, and bare patches inside a forest harvested areas.

Since use depends to a considerable extent on the characteristics of the land, there is a close relationship between LC and LU. Moreover, land characteristics influence the performance of a certain LU. However, LC and LU are not identical, and the knowledge of LC may not define LU. For example, vegetated areas are frequently described in terms of physiognomy and structure (e.g., different types of forest, woodland, grassland) without specification of their use as wildlands, plantations, agroforestry, protected wildlife habitats, revegetated mining areas, and so on.

Among concerns about global environmental change, the issues involved in LU and its changes over time are becoming increasingly recognized (Meyer and Turner 1994). While many environmental parameters affect the behavior of the earth's climate system and its terrestrial components, LU is a key descriptor of the human influence (Riebsame, Meyer, and Turner 1994; Veldkamp and Fresco 1996). For each parcel of land, individuals choose a type of use from which they expect to derive the most benefit considering a variety of things: their personal objectives and constraints; the given set of biophysical parameters; the institutional, cultural, and legal attributes of the land parcel;

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and the broader cultural and socioeconomic environment. As characteristics vary in space and time, so do LU choices, resulting in a spatial pattern of land use types.

In order to understand changes in the terrestrial environment and to be able to develop future scenarios, one must understand the considerations listed above. The planners of the International Geosphere-Biosphere Programme (IGBP) realized that alterations in LU would be the dominant driver of global change over the next few decades (Walker 1998). Changes in LU and LC comprise one of four major, large-scale environmental perturbations of the earth, together with biodiversity, atmospheric composition, and climatic changes (Walker and Steffen 1997). The need for an improved understanding of the interactions among natural processes and LU changes was recognized at a recent IGBP conference (Baulies and Canadell 1998) and has been the main impetus in establishing the IGBP Land Use and Cover Change (LUCC) project (Turner et al. 1999). Since LU is the result of the interactions between society and the natural environment, knowledge of it is crucial for the study and improved understanding of human-induced global changes and the institutional responses to them at all levels, from local to global (Pritchard et al. 1998).

The success of scientific studies of the above LU-related issues, as well as of numerous other research activities and policy initiatives, depends on the availability of timely and accurate LU information. At present there is lack of a global consensus on LU definitions and description (Di Gregorio and Jansen 2000). As a result, it is difficult to make existing local or regional LU data consistent over larger geographic areas of interest. This hampers a systematic approach to studies of LU-dependent processes (Jansen and Di Gregorio 1998b). For example, the largest information gap for the LUCC program occurs in the functional understanding and adequate parameterization of LU dynamics (Baulies and Szejwach 1997); baseline LU data are critical to filling this gap.

Spatial LU information has not previously been compiled in a systematic way over large areas, although numerous attempts at data collection have been made. Such attempts generally result in a mixture of LU and LC data (Jansen and Di Gregorio 1998a). The primary (and often only) generally available subcountry LU data are collected through census statistics, and thus do not show the spatial distribution of LC within the administrative unit. The fundamental problem in mapping LU is that LU typically does not leave a distinct signature that could be discerned without a site visit, possibly including in-depth socioeconomic/cultural surveys. It is often easier to see the results of a certain LU than the LU itself (Jansen and Di Gregorio 1998b). Since site visits are not feasible except for limited research and field checking purposes, this leaves the production of LU maps for large areas (e.g., $>10^3$ km^2) to another process.

In view of the above factors, the main strategy in the past has been to design a LU classification legend and to discern LU categories directly from remotely sensed images or other supporting data (Anderson et al. 1976; International Geographic Union 1976; Kostrowicki 1977; ECE-UN 1989; Jansen and Di Gregorio 1998a). This resulted in the incorporation to various degrees of LC aspects in LU legends. An example is the influential system for "land use and land cover classification" developed by Anderson et al. (1976). Although much progress has been made in LU mapping in this manner, the approach is limited to LU categories where the relation between LC and LU is strong and direct, and to those data types that are sufficiently detailed to contain discernible LU information. Both conditions imply constraints on the suitable data types to which and the geographic environments in which this approach can be applied.

In this article, we explore the relationship between land cover and land use, with the intent of using LC maps as the primary data source for the preparation of LU maps. The rationale for this approach is threefold. First, since LC and LU refer to different aspects of the land surface, they should be considered separately. This also facilitates response to different settings of geography, scale, land use characteristics, and available data sources. Second, LC maps are much easier to prepare because of the effectiveness of satellite remote sensing tools that facilitate observation over extensive areas at various spatial scales of both the current status and changes over time (FAO 1991; Bauer et al. 1994; Moran et al. 1994; Thompson 1996; Driese et al. 1997; Vogelmann, Sohl, and

Howard 1998; Cihlar 2000; Hansen et al. 2000; Loveland et al. 2000). LC information is frequently produced for various purposes and is also a key data set for LUCC (Turner et al. 1999), for global observing systems (GCOS 1997), for regional and national land use planning (FAO/UNEP 1997), and for other purposes. Third, as mentioned above, LC is an important determinant of LU, although the strength of the relationship between the two depends on a number of factors. First, we discuss the conceptual relations between LC and LU. Based on various classes of relationships, we then suggest ways in which the actual relationships can be determined in practice. Finally, we discuss the implications of our approach for LC and LU classification systems.

In the following discussion, we assume that the LC classification scheme consists of a number of discrete classes or cover types (see, e.g., Thompson 1996). This commonly used approach has limitations, because LC tends in fact to vary continuously (see, e.g., Lambin 1999). At present, a method of mapping continuous variables from which LC-type maps could be derived is at the research stage (see, e.g., DeFries, Townshend, and Hansen 1999). However, it is already clear that the particular LC scheme chosen will directly affect the resulting LU map. We also assume that a classification legend describing nonoverlapping LU classes (Table 1) can be designed for the geographic setting of interest. In principle, the type of legend and the definition of classes can be chosen to meet specific needs, and could include categories with multiple uses, etc. In general, land use may vary in space and time, multiple land uses may occur in the same area, and

Table 1 *Land Cover (LC) to Land Use (LU) Transformation of Classes in the Lebanon Case Study*

LC Classes	LU Classes	LC→LU[a]	Associated LCC[b]
1. Urban areas (built up)	A. Residential, industrial, mining, and recreation (mix of different uses)	3	1a, 7
1a. Urban areas (non–built up)			
2. Horticulture	B. Horticulture	1	
3. Field crops and fallow land (irrigated and nonirrigated)	C. Temporary cropping		
	C1. Irrigated temporary cropping	2	
	C2. Nonirrigated temporary cropping	2	
4. Trees and perennial crops	D. Permanent cropping		
4a. Olives	D1. Olive cultivation	1	
4b. Vineyards	D2. Grape cultivation	1	
4c. Deciduous fruit trees	D3. Fruit tree cultivation	1	
4d. Citrus or bananas	D4. Citrus and/or banana cultivation	1	
5. Grassland (unimproved land)	E. Extensive pasture or rangelands		
5a. Grassland and forbs from open to closed, or abandoned fields, or old fallows in agricultural areas	E1. Abandoned fields	3b1	
5b. Sparse grassland and forbs in mountains or desertic areas	E2. Natural/traditional grazing lands	3b2	5a, 6c
6. Forest and other wooded areas	F. Forestry (planted)		
6a. Coniferous forest	F1. Forest for production of pine kernels	3a	
6b. Deciduous forest	F2. Forest for re-afforestation	3b3	6a, 6c
6c. Scrubland and other types of degenerate forest			
	G. Natural forest uses		
	G1. Forest for recreational purposes	4	6a, 6b
	G2. Nonrecreational forest	3b1	6a, 6b
7. Unproductive land	H. Nonusages	2	7a, 7b
7a. Barren rocks			
7b. Highly dissected and eroded land			
7c. Beaches	Not analyzed		
8. Swamp vegetation	Not analyzed		
9. Water bodies	Not analyzed		

Sources: FAO (1991), Jansen, Latham, and Di Gregorio (2001).
[a] *The LC→LU relation follows the numbering used in this article.*
[b] *LC class(es) associated with the defined LU.*

the mixtures may change with time. Thus, representing land use using a classification legend with few basic categories may be an oversimplification in many situations. However, we do not envision that continuous fields of LU attributes can be developed in the foreseeable future.

Relations between LU and LC

Basic Considerations

As noted above, LC refers to the composition of the features of the earth's surface, LU to the type of human activity taking place at or near the earth's surface. LU is determined by many factors—natural, economic, institutional, cultural, and legal. In general, possible LUs are limited by biophysical constraints. These include climate, topography, soils and the geological substrate, presence or availability of water, and the type of vegetation. Frequently, these factors also find consistent expression in LC. For example, in the absence of disturbances natural vegetation develops in response to climatic and edaphic conditions of the region or landscape. The presence, type, and characteristics of vegetative cover are thus important indicators of the biophysical conditions. Similarly, open water, glaciers, and other cover types provide strong indications of the environmental conditions that have a bearing on potential LUs.

While environmental conditions provide important constraints on possible LUs, they are not necessarily decisive. Some types of LU are only weakly constrained, if at all, by the natural LC. This is especially true for those LUs that result in new LC: transportation infrastructure, buildings, dams, and so on. In such cases, the natural environmental constraints are mitigated by the investment of energy and materials necessary to make a particular LU possible. While the original LC is not important, the resulting one is fairly distinct and can be recognized through remote sensing techniques under appropriate conditions or by ground observation.

In addition to the above, LU is influenced by cultural factors. For example, agricultural practices differ from one region to another. Different types of LU are practiced on the same type of land in different areas, depending on the history, local traditions, and the way of life, aside from the biophysical constraints. For example, a study of four village areas in southern Mali revealed that different LU options were preferred in each depending on the village history and traditions and the people's religion. Time-series analyses of the areas also showed that land management decision making had changed from communal to individual LU (Jansen 1989). The location of the area with respect to other types of LU, such as residential and commercial areas, is also an important factor (Okoth 1998). For example, economic incentives—e.g., subsidies for certain crops—have influenced use of the land in Brazil, where sugarcane is grown over vast areas (Jansen 1990). Similarly, the common agricultural policy of the European Union has affected LU and cover patterns.

From the above discussion, it is evident that LC can be a cause, constraint, or consequence of LU. In the last-named case, the relationship is generally easy to establish and tends to be strong because the use of the structures is implied by their physical characteristics. When the modification of LC is less profound (e.g., if the change is not large enough to cause a shift from one cover type to another), the type of LU may be more difficult to infer and the reliability of the inference tends to be lower. The distinctions vary with the type of use, geographic region, and time. For example, crop LC is relatively easily mapped from remotely sensed data in most cases, provided that the sensor's spatial resolution is adequate. The type and intensity of management is much less evident, although it may be inferred given knowledge of local practices. Grassland may or may not be improved and may or may not be used as pasture, and open areas in a forest may have been harvested or burned. Similarly, multiple LUs are difficult to distinguish from LC alone (e.g., agroforestry practices). Note that these examples refer to situations where human activity either does not modify the natural appearance of the LC or modifies it in a way that is indistinguishable from changes made by other LUs. Thus, the degree of LC change resulting from a particular LU will depend on the LU practices in the area and must be determined in that context. Since LU practices change with time, by implication so may their relationship to LC. The LC/LU relation thus has a spatial as well as a temporal dimension, and one that must be carefully considered.

Specification of the LC→LU Mapping Function

When attempting to derive LU distribution from an LC map, the basic challenge is to specify the function

$$LU_i = f(LC_j, e_1, \ldots, e_n, sc_1 \ldots, sc_n), \quad (1)$$

where e and sc represent environmental and socioeconomic/cultural variables respectively, and i and j are specific LU and LC types.

The various factors in Equation (1) are not of equal importance in all situations. Distinctions can be made according to the size or other attributes of the area under consideration and the variability of the parameter under consideration. For example, factors constraining LU will be different at a continental than at a local level; climate will be an important factor in the first case, topography in the second. Topography will play a key role in a hilly terrain, but not on a floodplain. Similarly, cultural variables may differ among regions or countries, but they are less likely to be highly significant locally. To give another example, the LU of a given patch may be decisively influenced by the LU of adjacent patches. This is true for a hilly terrain, or for various types of urban LUs that tend to co-occur. Thus, it should be possible to define a structured approach to the specification of the LC→LU function.

The relation between LC $= j$ and LU $= i$ (Equation [1]) may or may not be unique. Four cases are possible:

- Case 1: for each LU_i there is only one corresponding LC_j such that $a_{ij} = 1$ (see Equation [2]); i.e., a 1:1 relationship (Figs. 1 and 2). For example, a built-up cover type corresponds to urban land use.
- Case 2: for each LU_i there is more than one LC_j such that $a_{ij} = 1$; i.e., 1 LU:several LC (Figs. 1 and 2). For example, corn and wheat fields correspond to agricultural land use.
- Case 3: for each LC_j there is more than one LU_i such that $a_{ij} = 1$; i.e., several LU:1 LC (Figs. 1 and 2), but this relationship holds across the spatial domain of interest. For example, shrub cover within forest corresponds to harvested trees or fire scars. This category is further discussed below.
- Case 4: for a given LC_j there is more than one set of LU_i for which $a_{ij} = 1$; i.e., several LU:1 LC (Fig. 2). This relationship varies within the domain; that is, various combinations of LU_i are associated with a given LC_j.

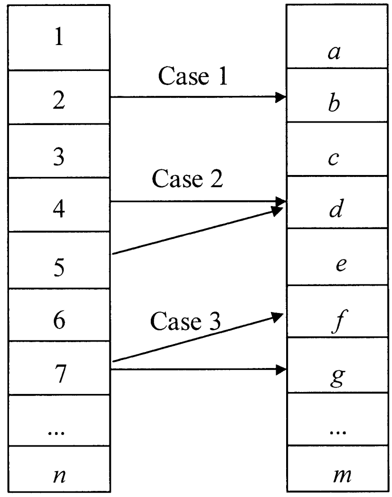

Figure 1 *Basic logical relations between land cover (LC) and land use (LU).*

Case 3 is complicated because LC→LU relations are of two different types, thematic (type of LC or LU) and spatial (i.e., the spatial arrangement). Thematic relationships (Fig. 3a) can be represented in a transition matrix and do not depend on the spatial distribution of the two types. Spatial relationships (Fig. 3b) are evident from a comparison of two maps for the same area. Two basic possibilities can be distinguished:

- Case 3a: A given LC_j is always associated with one fixed set of LUs ($LU_{i1}, \ldots, LU_{in}$, $n \geq 2$) (Figs. 2 and 3), and the various LUs are uniformly distributed (e.g., forest used for timber and cattle grazing).
- Case 3b: A given LC_j is associated with various sets of LU_is (Figs. 2 and 3). Furthermore, the relationship LC_j vs. LU_is holds across the spatial domain of interest (e.g., built-up area is always residential or industrial, etc.).

Three possibilities exist for case 3b (Figs. 2, 3b), on the basis of the spatial LC→LU relationship within individual LC parcels and their boundaries.

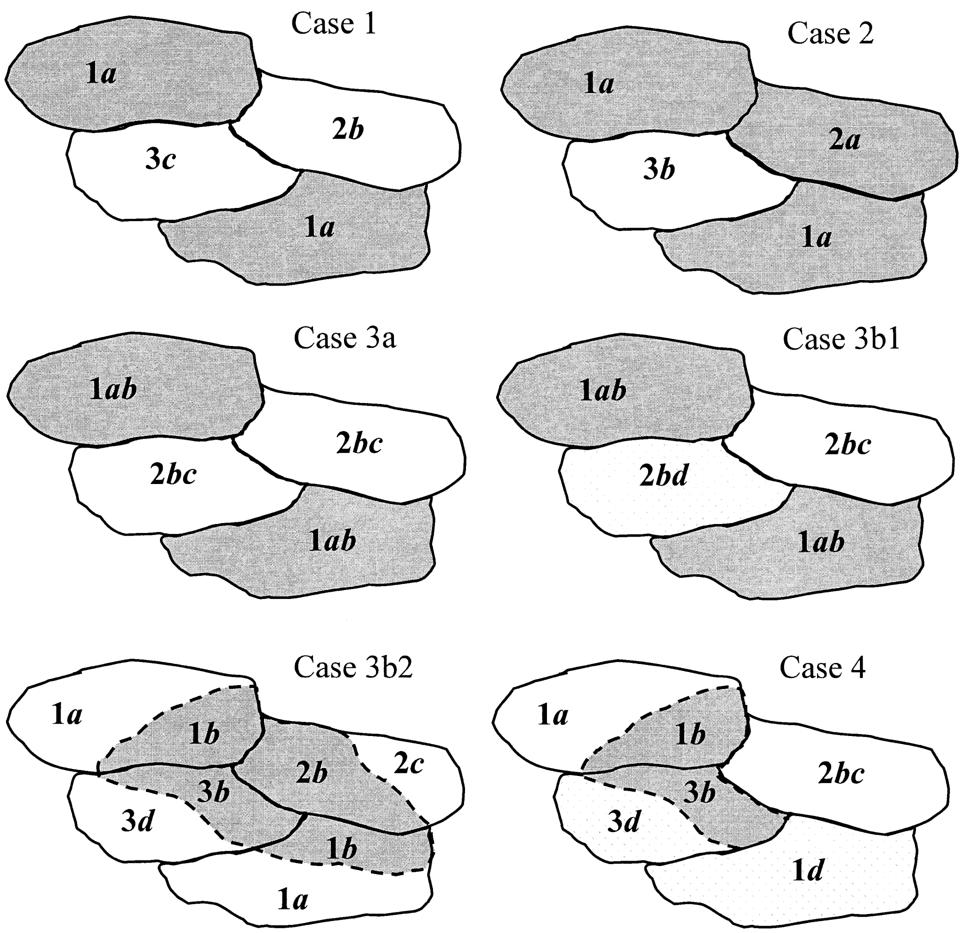

Figure 2 *Possible combinations of land cover (LC) and land use (LU) mapping boundaries. In each polygon, the number represents a LC type, the letter(s) a LU type(s).*

- Case 3b1: The condition of coincident LC/LU boundaries is not violated. That is, individual parcels of LC_j may be assigned to various LU_i combinations in different parts of the domain, but in each case the LU_i combination applies across the entire individual parcel. For example, in Figure 2, LC_1 is always associated with (LU_a + LU_b). Case 3b1 is therefore similar to 3a, except that multiple LU_i sets are possible.
- Case 3b2: The condition of coincident LC/LU boundaries is violated. Thus, a given parcel with LC_j contains more than one LU type LU_i, with LU boundaries not coinciding with LC boundaries (Fig. 2). However, the relationship LC_j/LU_i is consistent across the domain of interest.
- Case 3b3: This is a combination of cases 3b1 and 3b2. The relation LC_j/LU_i holds for all parcels *j* but may or may not hold inside these parcels.

It should be noted that the thematic LC/LU relationship is the same for cases 3b1–3b3 (Fig. 3a); the differences are due to spatial relationships.

Case 4 is the most complex one (Figs. 2 and 3b). Here the LC/LU relationship is not well defined because LU does not depend or depends weakly on LC. Thus, a given LC = *j* is associated with various combinations of LU,

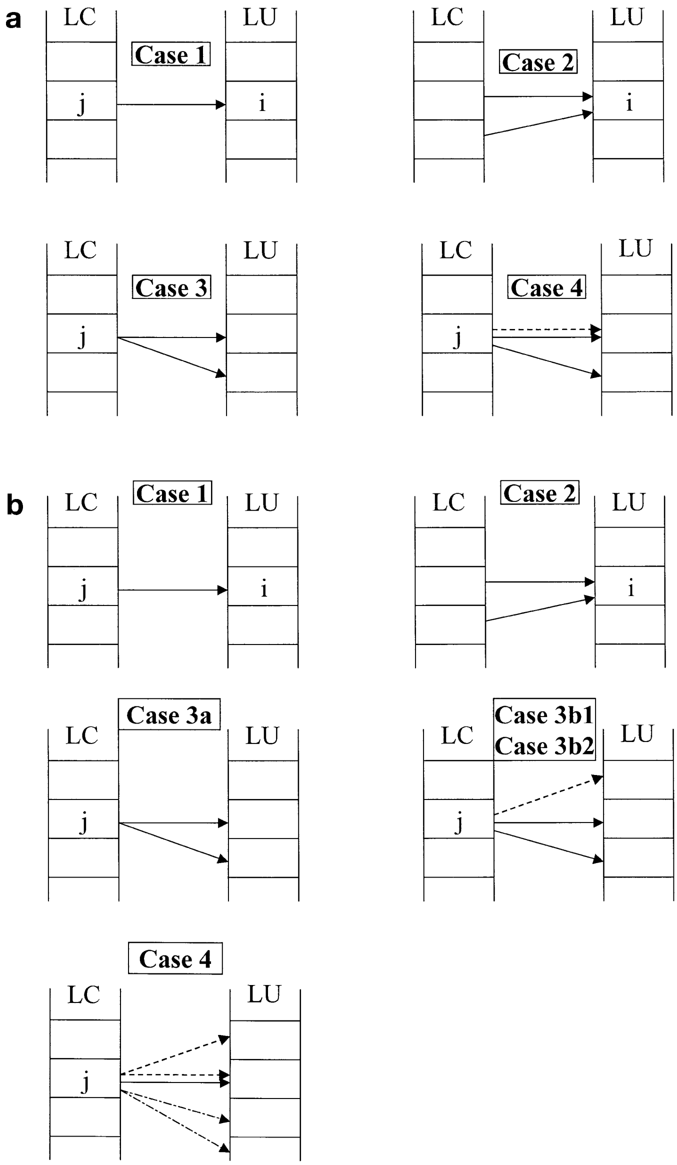

Figure 3 *Conceptual thematic (a) and spatial (b) relationships between land cover (LC) and land use (LU) mapping units.*

both within and among land parcels *j*. Case 4 is a mixture of cases 1, 2, and 3 applied to a specific LC_j. This is likely to occur when the LU classification scheme is very detailed in comparison to the LC classes.

Based on the above characterization, three different types of LC→LU relationship can be considered (Fig. 4):

- Type 1, in which the relationship is thematically and spatially unique;
- Type 2, in which the relationship is not thematically unique but is spatially consistent throughout the domain of interest; and
- Type 3, in which the relationship is not thematically unique and not spatially consistent.

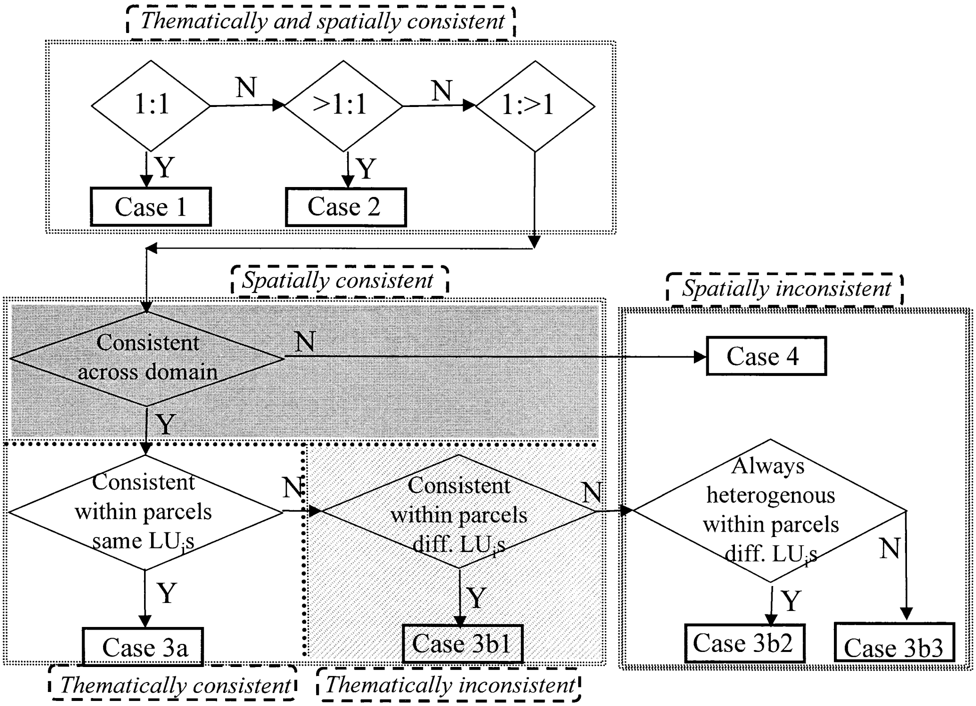

Figure 4 *Decision tree for labeling land use (LU) vs. land cover (LC) relationships as cases 1–4.*

The structure in Figure 4 accommodates cases 1 to 4 and illustrates the progressively weaker association between LC and LU. It is important to realize that, for a given domain of interest, a particular LU_i may belong to any of the combinations in Figure 4, and that its location may vary over time for that domain as well as among various domains of interest.

Tools for a Solution

Given an LC map, the desirable way to obtain a first approximation of a LU map is to define the LC→LU transformation. Using Figure 4 as a guide, the following simplifications can be made.

Cases 1, 2, and 3a. When LU boundaries do not cross LC boundaries, the simplest mapping function is

$$LU_i = a_{ij} \times LC_j, \qquad (2)$$

where $a_{ij} = 1$ for only one combination of (i,j). That is, a given LC $= j$ has a corresponding LU $= i$.

For cases 1 and 2, a cover type j can be assigned to only one LU type i. Thus, only the relation $LC_j \rightarrow LU_i$ needs to be determined from field data and validated with an independent sample. This will normally be the case when LU is clearly associated with LC type. As a simple case, built-up areas imply urban LU. Such relation can also be established with confidence in potentially confusing situations. For example, a parcel of grass in a cultivated area is very likely pasture, not natural grassland. Through this process, a transition matrix with LC (rows) and LU (columns) will be prepared. Once such a table is available, an LC map containing cases 1 or 2 can be readily transformed into an LU map.

In Case 3a, there are two or more combinations (i,j) for which $a_{ij} = 1$ (Equation [2]). Nevertheless, the situation is again fairly simple because the LC/LU relationship is effectively the same as for cases 1 and 2. This is obvious if one considers the combination $(LU_{i1}, \ldots, LU_{in})$ as another LU type. It is thus a special example of case 1.

Case 3b. Case 3b is more difficult, even though the a_{ij} values (equation [2]) may be identical to those in case 3a. Here the LU boundaries cannot be obtained from the distribution of LC alone, as they may lie entirely within existing LC parcels (case 3b1, Fig. 2) or cross LC parcel boundaries (case 3b2, Fig. 2). The LU boundaries thus subdivide or combine existing LC parcels. To determine their position, additional information must be employed. This information may apply to all such parcels (case 3b1) or individually to each parcel (3b2).

For case 3b1, the solution is again relatively straightforward. The mapped LC parcel boundaries can be used to obtain an LU map. The additional information required is the values of a_{ij} for each LC_j, realising that $a_{ij} = 1$ for several *i*s. For case 3b2, additional spatial information is required; some possibilities are discussed in section 2.4.

Case 4. Since the relation LC vs. LU is weak or nonexistent in this situation, the values of a_{ij} must be determined using other information for each parcel of LC_j to which case 4 applies.

Supplementary Sources of LU Data

Given an LC map, the most expedient approach is to make the maximum possible use of this map and then add further information. Three possibilities of increasing complexity are offered below.

(a) *Re-examine the classification scheme*. The first consideration is whether the problem can be avoided by modifying the applied LU classification scheme. It is possible that the intended LU distinctions are not absolutely necessary, or not worth the cost of acquiring the data to make the differentiation.

(b) *Image interpretation*. Assuming that the LC map was prepared through analysis of remotely sensed data (airborne or satellite), it is possible to obtain LU information in addition to LC. While LC is based primarily on spectral data content (which makes the successful use of digital image analysis possible), LU information benefits from other aspects of the data including pattern, shape, context, size, shadows, etc. This contextual information may be efficiently extracted using visual analysis (Rabben 1960). A skilled interpreter, familiar with the LC and use types in the area, can obtain important additional LU information and may thus be able to identify LU boundaries within the image (suitably enhanced for optimal viewing). This aspect was used with great advantage by Anderson et al. (1976).

(c) *Adding variables*. A more comprehensive approach to defining the LC→LU relation in cases 3b and 4 involves adding other independent variables. For example, environmental parameters such as slope and aspect (through digital terrain models) or soil properties may be added relatively easily. Such variables must be selected carefully, based on their ability to differentiate between various possible combinations of LC_j and $LU_1, \ldots, LU_k$. The specific variables will depend on the characteristics of the area and the particular LC/LU_is combination. Land ownership is a critical variable, and its availability in georeferenced format will in most cases greatly increase the quality of the land use map. Unfortunately, these data are often not generally available. In general, the objective is thus to define the function $LU_i = f(LC_j, V1, \ldots Vn)$, where f specifies the unique relation LC_j vs. LU_i with the help of variables Vk, the latter representing any of the variables in Equation (1).

In principle, additional information need be obtained only for those LC_js to which cases 3b2, 3b3, or 4 apply. However, depending on the type of variable, it may be easier to obtain it for the entire mapped area.

One convenient way of using additional variables is a look-up table approach. Because the processes leading to individual LUs are not generally well understood or quantified, the simplest approach is based on decision rules. For example, Vk in the range $<Vk_{\min}, Vk_{\min+l}>$ (where l is an empirically established threshold) implies one LU type, and so on. Conceptually, this means dividing the range $<Vk_{\min}, Vk_{\max}>$ into two or more intervals, each associated with a specific cover type. However, several variables Vk may be required to define Equation (1) for a particular LU_i. The range occupied by LU_i will then be delineated in an n-dimensional space. It should be noted that individual LU_is may have overlapping ranges and that they may not use the same set of variables Vk. Nevertheless, all LU_is can be located within this multidimensional space, in which the number of dimensions equals the number of variables Vk and the maximum number of entries equals the product of the number of possible values of each Vk.

In practice, it will be necessary to establish the LU_i segment for each variable Vk, thus defining the range it occupies in the n-dimensional space. This can best be accomplished by obtaining a representative sample of data for each LU_i, together with the values of all the variables Vk. Note that not all variables need to be determined for a given LU_i. Variables for which a range is not defined are considered not to be diagnostic for that LU_i. Since the dependencies between LU_i and the variables Vk are not always well understood, the delineation of the range for a LU_i may have to be done iteratively until a satisfactory description of the decision space is obtained.

The variables Vk may have several forms. These could range from a class/category (A, B, C, . . .), to a rank (low, medium, high), to a simple continuous variable (e.g., elevation), to a complex continuous variable derived by combining two or more primary variables (obtained through a regression model, for example). The choice should be pragmatic, guided by the need to differentiate accurately between the various LC_j/LU_is combinations. The choice will depend on the constraints determining the LU/LC relationship in a particular setting. Once the decision rules are completed, their application is the same as for cases 1, 2, and 3a: the required variables must be determined for the mapped area and the look-up table then applied. This process should yield an *LU* map for all cover types.

It should be noted that cases 1, 2, and 3a are reduced forms of cases 3b, 3c, and 4. In these situations, the ranges for the individual LU_is (that is, values $<Vk_{\mathrm{i,min}}, Vk_{\mathrm{i,max}}>$ for a particular LU_i) are identical to the entire range $<Vk_{\min}, Vk_{\max}>$ for all variables k. In other words, the relationship holds for any combination of values Vk because the spatial boundaries of the two types of units coincide. The complexity of the LC/LU relationship will strongly depend on the characteristics of LU and of the LU classification scheme adopted. If the latter is very simple, cases 1 and 2 will be more frequent and the LC→LU task will be much easier.

An Example of Application

In 1996–97, the Food and Agriculture Organization of the United Nations (FAO) undertook a national case study to obtain LU classes from a remotely sensed data–derived LC map (Jansen, Latham, and Di Gregorio 2001). Spatial LU information often does not exist in countries, while LC information is mostly present in the form of maps derived from remotely sensed data. The FAO selected Lebanon for its case study because, in spite of the country's limited area, it offered a wide variety of LC types due to the variety in landforms and variability in rainfall. This created a challenge when trying to develop a set of decision-rules to derive the dominant LUs from the existing 1:50,000 scale LC map derived from remotely sensed data (FAO 1991). The development of a set of decision-rules that would allow such a transformation brought several problems to light concerning spatial and temporal variation of LC over time, the accuracy of the input materials, the limitations of the developed decision-rules, and the complexity of the relation between LC and LU (Jansen, Latham, and Di Gregorio 2001).

Based on the existing LC map and ancillary data, *a priori* LU classes were defined for a preliminary transformation of LC mapping units into the *dominant* LU classes. A stratified random sampling scheme was developed for the LU field sampling that took into account the complexity of the mapping units—that is, the cooccurrence or not of LC and LU polygons. Based upon the sampling scheme, field validation and collection of additional information on the LU parameters was carried out. The results of the field campaign were used to modify the defined a priori LU classes. In addition, observations at 116 locations were collected separately for validation purposes. The set of decision-rules being used was tested in a part of Lebanon before being applied to the whole territory. These decision-rules took into account available additional digital databases containing information on such areas as elevation, infrastructure, protected areas, irrigation schemes, urban areas, and towns, provided by the Geographic Affairs Division of the Lebanese Army, the Ministry of Agriculture, the National Council for Scientific Research, and the Ministry of Hydraulic and Electric Resources.

The original nine LC classes and subclasses were interpreted in LU terms (Table 1). Three different types of analysis were used for the preliminary interpretation (Jansen, Latham, and Di Gregorio 2001):

- *Direct conversion:* Existing LC classes were selected and converted straight into a LU class (e.g., LC class "Urban areas" was put into the LU class "residential, industrial, mining, and recreation [mix of different uses]"). In these situations, the mapping boundaries concur with the LU boundaries and the relation between LC and LU is 1:1 (case 1).
- *Associative method:* Selected LC classes were intersected with additional spatial digital data layers (e.g., elevation or irrigated areas) to derive the LU class. This implies that the boundaries of LC and LU do not necessarily concur and that more than one LU may be present; the LC/LU relation is one to many (cases 2 or 3a).
- *Deductive method:* LU classes were determined based upon assumptions made due to lack of sufficient additional data. In these classes, the LC information does not have a direct relationship with LU(s) and confidence levels are lowest. The LC/LU relationship may be 1:1, 1:many, or many:1 (case 3b or 4).

Correlation between certain LC and LU classes showed that for some classes the LU interpretation is straightforward (especially LU classes "residential areas," "horticulture," and "permanent cropping"), while other classes needed additional spatial data layers. For distinguishing irrigated and nonirrigated classes in the "field crops and fallow land" LC class, the associative method was used: that is, a data layer showing irrigated areas of Lebanon compared to the original LC map made it possible to distinguish the two LU classes. For other classes, the LC data was of limited use in trying to infer LU. This was especially true for the forested areas of the LC map; these are subdivided according to leaf phenology (coniferous and deciduous) or difference in vegetation structure (scrubland), and such terms do not readily indicate how these areas are being used (LU classes "forestry [planted]" and "Natural forest uses"). This case required a deductive analysis relying on a set of assumptions, established facts, or local expertise in order to logically deduce the proper dominant LU class.

The original LC map (FAO 1991) also contained information on LU. This was particularly helpful in identifying the LU class "extensive pasture or rangelands." However, identification of LU class "abandoned fields" using the available information proved to be difficult. Review of the history of Mount Lebanon (Mikesell, 1969) and local knowledge showed that below the altitude of 1500 m very few pastures and rangelands exist, as most suitable lands have been used for agriculture. Those that are not used belong to scrubland or degenerate maquis. The assumption was made that all areas below 1500 m and coded as LC class "grassland and forbs from open to closed, abandoned fields, or old fallows in agricultural areas" would be classified as abandoned fields. The same assumption was made for the mixed LC classes of grasslands with agriculture. During the civil war, many cultivated fields were abandoned. The LU class "natural/traditional grazing lands" included those LC classes excluded from LU class "abandoned fields."

In theory, the collected LU field samples can be used in two ways: (1) to infer the LU from the LC mapping unit (establishing the decision-rules); and (2) to verify the LU classes generated by the set of developed decision-rules (testing the rules). In this case, the 116 field samples were put to the latter use, utilized to verify the generated LU classes and to test the soundness of the developed set of decision-rules. The accuracy levels of the classes derived through the associative and deductive methods outlined above were found acceptable (63.8 percent agreement on average). The LU classes derived through direct conversion, or inference, had the highest accuracy levels. The case study showed that LU classes can be derived from a remotely sensed data-derived LC map, but that the field survey is crucial in providing a sound sample set to test the decision-rules. Numerous samples are needed, especially for LUs whose relation with LC is not 1:1 (Jansen, Latham, and Di Gregorio 2001). For the LUs where it could be stated a priori that the expected relation would not be 1:1, a proper sample set is needed. These LUs include forest uses and grazing land classes.

Implications for LU Mapping and Classification

In principle, a LU mapping scheme over large areas could be constructed in two ways: bottom up or top down. In the first case, one would need to make a complete inventory of all the possibilities over the area and then structure these into a coherent classification legend. In the second case, one would start with a dataset/ scheme that could be obtained over the entire area and then subdivide this in terms of LU differences. The difficulty in categorizing LU is that it consists, in theory, of a number of momentary actions undertaken over time. Land use in itself is not an object that one can describe or delineate. Thus the main strategy is to ascertain, not an action itself, but the results of an action.

Since distinct LU often takes place over small patches of land, LU mapping implies a large mapping scale and, in remote sensing terms, small pixels—say, 20–30 m, which corresponds approximately to a mapping scale of 1:50,000. At coarser mapping scales, it is unlikely that individual patches of LU can reliably be resolved, although this will clearly depend on the type of LU; for example, extensive LUs such as wildlands do not pose such restrictions. In practical terms, then, the issues in mapping LU in a given area are:

1. What LUs occur in this area, and what are their spatial characteristics—especially patch size?
2. How do the individual LUs relate to the respective LC characteristics?

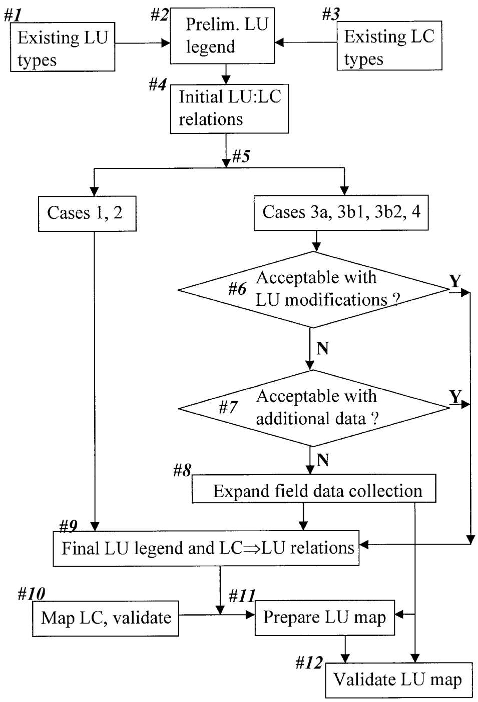

Figure 5 *Application of the LC→LU methodology to mapping land use (LU) over a hypothetical large area.*

Figure 5 illustrates a conceptual approach to mapping LU in a geographic area based on the concept put forth in this article. The implied objectives are twofold: mapping accuracy sufficient for the purpose for which the project is undertaken, and practical feasibility. Information on LU types in the area (step #1) may be obtained from census data, field surveys, or other sources. These provide an inventory of the possibilities that need to be accommodated in a LU legend and can be used to prepare the preliminary legend (#2). A review of the LC characteristics and of available remotely sensed data sources, with some preliminary analysis, yields a list of distinguishable LC types (#3). Alternatively, LC maps may already exist. Based on this knowledge of LU and LC types to be expected in the area, the LU→LC relationships can be identified (#4) and their spatial and thematic characteristics determined (#5).

In principle, only cases 1 and 2 are dealt with at this stage. For the others, the next step (#6) is to examine the question of whether the confusion due to cases 3–4 is important, to identify the minimum number of LU/LC relationships that must be differentiated in this step, and to determine whether the LU legend (#2) can be modified in an acceptable way to transform cases 3–4 into cases 1–2. If these measures do not change all cases 3–4 into 1–2, the next step (#7) is to search for readily obtained additional information that achieves the same result for the minimum number of LU→LC relationships identified in #6. Such information might come from remote sensing data (e.g., human interpretation based on contextual clues), available spatial databases such as digital elevation models, other ecological information available as maps, or other sources. If some information sources are found, their impact should be examined to determine if, with a possible further reduction of the minimum number of LU→LC cases needed, all cases 3–4 could be eliminated. Failing that, the field survey should be expanded (#8) so that the required observations are available for the LU map. Based on steps #5 to #7, a final set of LU/LC relations that contains the desired LC→LU transformation rules can be obtained and used (#9). The next steps are relatively straightforward: mapping LC from remotely sensed data (#10), including its validation; transforming this map into a LU map (#11), with the aid of field data from #8 as required; and evaluating the accuracy of the LU map (#12).

In preparing and modifying the LU legend (#2, #6, #7, Fig. 5) certain considerations should be kept in mind. First, the legend is a subset of a LU classification system and thus should conform to general principles of classification (Table 2). Second, it should be organized hierarchically to offer a high degree of flexibility and the ability to accommodate different levels of information. Such a classification system can be applied at various scales, from local to global (Jansen and Di Gregorio 1998b). Third, the classification should contain those parameters that form criteria important for LU categorization, while environmental descriptors (e.g., soils, landforms, and altitude) should be avoided because they describe the setting of the LU rather than the use itself. In addition, the definition of LU classes should partially deal with the variation over time (e.g., cropping systems describe the various phases of crop establishment dependent on the type of crop), but LUs that follow each other over time—and that may even overlap—should be treated as individual LUs on the same spatial basic unit. This leads to "multiple LUs" (Duhamel 1998). Finally, the ability to reduce the level of detail in LU classification is likely to decrease the cost of the LU mapping task.

Table 2 *Set of Principles for a Classification System*

Completeness, i.e., all occurring land uses should be covered by the system
Absence of overlap between classes because they should be mutually exclusive
Observation unit should be well-defined and explained
Tool independent, because otherwise the method of observation would a priori exclude certain classes
Definitions and explanatory notes should accompany the classes
Interpretation rules of how to decide what is which class
Index of objects that are contained in the system
Correspondence with other systems should be mentioned, if applicable

Source: Duhamel (1998).

Comments

The information on LC and LC→LU that can be extracted from remotely sensed data is determined by the characteristics of the data, including its spatial and spectral resolution, availability of stereo (in three dimensions), and others. This means that if the source data are predetermined, the expected LU classes will be constrained accordingly. As a simple example, at a resolution of 10 km only broad LU classes will be possible, with many pixels in reality containing various land uses. This LU complexity cannot be captured for practical reasons and it has to be assumed that cases 1, 2, and 3a prevail—that is, that the boundaries of LC and LU polygons coincide. For mapping activities where cases 3b, 3c, and 4 are important, the approach should be first to identify the LC/LU relationships that occur in the domain of interest. The spatial and thematic aspects of these relationships—in our figures, the respective sizes and distributions of LC and LU polygons—will determine the most appropriate data types and suggest the way they may be best used. Given the variety of environmental and human-related factors that result in a given land use (cf. Equation [1]), the LC/LU transformations are also likely to be nationally/regionally specific.

It is apparent that if the two approaches outlined above are applied to the same geographic domain, they are likely to yield two different LU maps. In other words, the approaches are not generally compatible. Since the LC/LU transformations are scale- and geographic area-specific, it may also not be feasible to develop hierarchical schemes. Rather, each situation must be considered on the basis of either available data, thus constraining the richness of the LU information, or the desired degree to which the complexity of the LC/LU relations is to be portrayed. In the first case, the analyst has some flexibility through the design of the LC classification scheme. Here the objective should be to construct classes that reflect, to the degree possible, the differences in LU. The system described by Anderson et al. (1976) is an example of this type.

The conceptual scheme described in this article is also relevant for the mapping of land use change. It implies that two phases are required: mapping of changes in land cover and determination of changes in the LC/LU relationship. While the former can be established through an analysis of remotely sensed data, the latter depends on determining changes in the LC/LU relationships during the period of interest. ■

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